New Security Results on Encrypted Key Exchange

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Summary

- Contributions of this talk
  - Encrypted Key Exchange – example
  - Security Results
- One-Mask Diffie-Hellman Scheme
  - Password-based Authentication
  - Security Model
  - Analysis of the Protocol
  - Properties – Denial of service
- Conclusion

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Key Exchange Schemes

- Alice and Bob agree on a common secret key sk, in order to establish a secret channel
- Intuitively: implicit authentication
  - only the intended partners can compute the session key
- Formally: semantic security
  - the session key sk is indistinguishable from a random string r, to anybody else

Example: Diffie-Hellamn

- Diffie-Hellman Key Exchange
  - G=<g>, cyclic group of prime order p
  - Alice chooses $x \in Z_p$ and sends $X=g^x$
  - Bob chooses $y \in Z_p$ ans sends $Y=g^y$
  - Both can compute $K=g^{xy}$
- (Passive) Security under DDH Assumption
- No security against active adversaries
  - Authentication is needed

How Authentication is Done

- Asymmetric: (sk_A, pk_A) and possibly (sk_B, pk_B)
  - they authentify to each other using the knowledge of the private key associated to the certified public key
- Symmetric: common (long / high-entropy) secret
  - they use the long term secret to derive a secure and authenticated ephemeral key sk
- Password: common (short / low-entropy) secret
  - let us assume a 20-bit password

EKE - AuthA

Alice	Password π	Bob
$x \in \mathbf{Z}_q$, $X = g^x$	Alice, $X' = \mathbf{E}_\pi(X)$ →	
		$X = \mathbf{D}_\pi(X')$
$Y = \mathbf{D}_\pi(Y')$	← Bob, $Y' = \mathbf{E}_\pi(Y)$	$y \in \mathbf{Z}_q$, $Y = g^y$
$K = Y^x$		$K = X^y$
	$sk = H(\text{Alice}, \text{Bob}, X, Y, K)$	

EKE

Bellovin-Merritt 1992

Two-flow Encrypted Key Exchange

AuthA

Bellare-Rogaway 2000

OEKE = One-flow Encrypted Key Exchange

Alice	Password π	Bob
$x \in \mathbf{Z}_q$, $X = g^x$	Alice, X →	
$Y = \mathbf{D}_\pi(Y')$, $K = Y^x$	← Bob, $Y' = \mathbf{E}_\pi(Y)$	$y \in \mathbf{Z}_q$, $Y = g^y$
$k_1 = H_1(\text{Alice}, \text{Bob}, K)$	k_1 →	$K = X^y$
		k_1 correct ?
	$sk = H(\text{Alice}, \text{Bob}, X, Y, K)$	

- Both schemes used an ``ideal cipher´´

New Results

- Provable security is achieved for both EKE and AuthA
  - In the random oracle model only
  - Based on CDH assumption
- Which means…
  - Security against dictionary attacks
  - Semantic security of the session key
- Add Denial-of-Service protection

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Password-based Authentication

- Password (short / low-entropy secret – say 20 bits)
  - exhaustive search is possible
- Basic attack: on-line exhaustive search
  - the adversary guesses a password
  - tries to play the protocol with this guess
  - failure $\Rightarrow$ it erases the password from the list
  - and restarts…
- after 2^{20} attempts, the adversary wins

Dictionary Attack

- The on-line exhaustive search
  - cannot be prevented
  - can be made less serious (delay, limitations, …)

We want it to be the best attack…

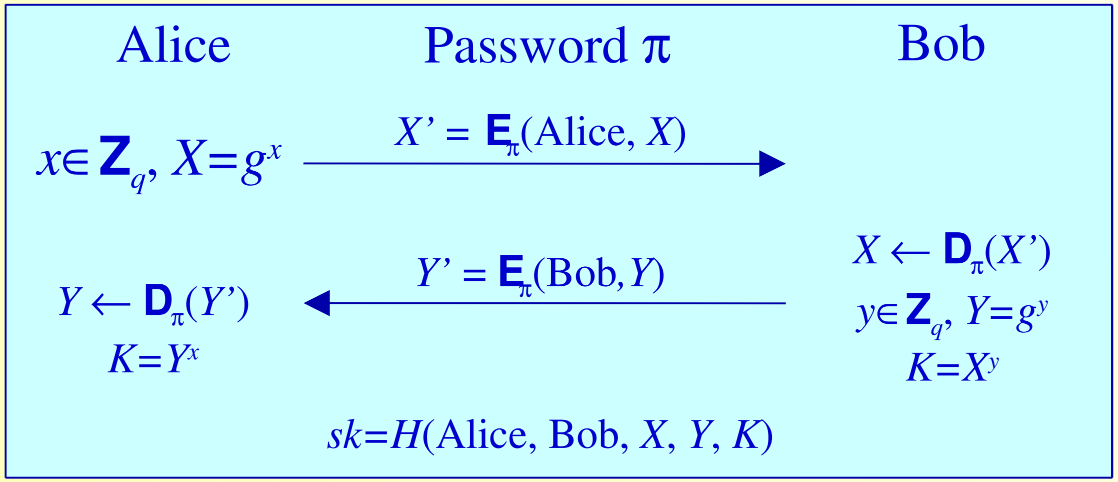
- The off-line exhaustive search
  - a few passive or active attacks
  - failure ⇒ erasure of MANY passwords from the list
  - this is called **dictionary attack**

Example: EKE

- The most famous scheme EKE:

  Encrypted Key Exchange
- 2 flows are encrypted with the password.
- Must be done carefully: ***no redundancy***
- For each password π
  - decrypt X'
  - check whether
    it begins with "Alice"

bad one !



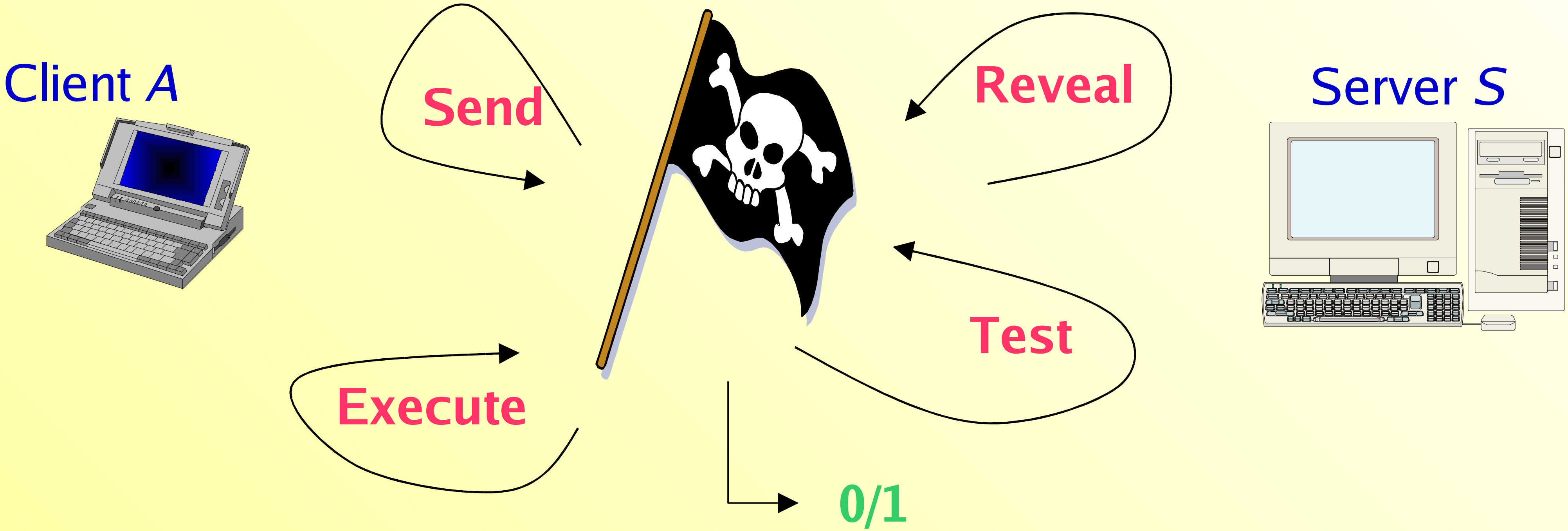
One-Mask Diffie-Hellman KE

Client A	Password π and $\Pi = G(\pi)$	Server S
$x \in \mathbf{Z}_q,\ X = g^x$	Alice, $X^* = X.\Pi$ $\longrightarrow$	$X = X^*/\Pi$ $y \in \mathbf{Z}_q,\ Y = g^y$ $K = X^y$
$K = Y^x$ Auth$s$=? $H(A,S,X^*,Y,\Pi,K)$	$\longleftarrow$ Bob, Y, Auth$s$	Auth$s$= $H(A,S,X^*,Y,\Pi,K)$

$$\boxed{Sk = H'(\mathrm{A,S,X^*,Y,\Pi},\ K)}$$

Security Model

As many **Execute**, **Send** and **Reveal** queries as the adversary wants



But one **Test**-query, with b to be guessed...

Passive/Active Adversaries

- Passive adversary: history built using
  - the Execute-queries ⇒ transcripts
  - the Reveal-queries ⇒ session keys
  - must learn *no information* about password
- Active adversary: entire control of the network
  - the Send-queries ⇒ send arbitrary messages
  - a Send-query allows to erase at most one password from the list

Semantic Security

- For breaking the semantic security, the adversary asks one Test-query which is answered, according to a random bit b, by
  - the actual secret data sk (if b=0)
  - a random string r (if b=1)
- $\Rightarrow$ the adversary has to guess this bit b

OMDHKE: New Security Result

- Assumptions
  - the random-oracle model – for G, H and H1
- Notations
  - q_s, the number of Send-queries (active and adaptive)
  - q_h, the number of Hash-queries to G, H and H1
  - N, the number of passwords
- Semantic security of DHKE :

advantage $\geq 12q_s/N + \varepsilon$,

$\Rightarrow$ CDH problem : probability $\geq \varepsilon/qh^2$

(within almost the same time)

One-Mask DHKE: the Proof

Client A Password π and Π=G(π) Server S

$x \in \mathbf{Z}_q$, $X^* = g^x$

$\xrightarrow{\text{Alice}, X^* = X.\ \Pi}$

$X = X^*/\Pi$

$y \in \mathbf{Z}_q$, $Y = g^y$

$K = X^y$

$K = Y^x$

$\xleftarrow{\text{Bob}, Y, \text{Auth}s}$

Auth$s$= H$(A,S,X^*,Y,\cancel{\Pi,K})$

Auth$s$=? H$(A,S,X^*,Y,\cancel{\Pi,K})$

$\boxed{sk = \mathrm{H}_1(A,S,X^*,Y,\cancel{\Pi, K})}$

The Proof (2)

Client A Password π and $\Pi = G(\pi)$ Server S

$x \in \mathbf{Z}_q,\ X^* = g^x$ $\xrightarrow{\text{Alice},\ X^* = X.\ \Pi}$ $\cancel{X = X^*/\Pi}$

$y \in \mathbf{Z}_q,\ Y = g^y$

$\cancel{K = X^y}$

$K = Y^x$ $\xleftarrow{\text{Bob},\ Y,\ \text{Auth}s}$ $\text{Auth}s =$

$\text{Auth}s = ?$ $H(A, S, X^*, Y, \cancel{\Pi, K})$

$H(A, S, X^*, Y, \cancel{\Pi, K})$

$\boxed{sk = H_1(A, S, X^*, Y, \cancel{\Pi, K})}$

The Proof (3)

Client A	Password π and Π=G(π)	Server S
$x \in \mathbf{Z}_q$, $X^* = g^x$	Alice, $X^* = \cancel{X \cdot \Pi}$ $\longrightarrow$	$\cancel{X = X^*/\Pi}$ $y \in \mathbf{Z}_q$, $Y = g^y$ $\cancel{K = X^y}$
$K = Y^x$ Auth$s$=? H$(A,S,X^*,Y,\cancel{\Pi,K})$	$\longleftarrow$ Bob, Y, Auth$s$	Auth$s$= H$(A,S,X^*,Y,\cancel{\Pi,K})$

$$\boxed{sk = \mathrm{H}_1(\mathrm{A,S,X^*,Y},\cancel{\Pi, K})}$$

The Proof (4)

Client A	~~Password π and Π=G(π)~~	Server S
$x \in \mathbf{Z}_q$, $X^* = g^x$	Alice, $X^* = \cancel{X \cdot \Pi}$ $\longrightarrow$	$\cancel{X = X^*/\Pi}$ $y \in \mathbf{Z}_q$, $Y = g^y$ $\cancel{K = X^y}$
$K = Y^x$ Auth$s$=? H$(A,S,X^*,Y,\cancel{\Pi,K})$	$\longleftarrow$ Bob, Y, Auth$s$	Auth$s$= H$(A,S,X^*,Y,\cancel{\Pi,K})$

$$\boxed{sk = \mathrm{H}_1(\mathrm{A,S,X^*,Y,}\cancel{\Pi, K})}$$

One-Mask DH Key Exchange

- The simulated execution is indistinguishable from the real one, unless:
  - adversary asks the random oracle on values such as (A, S, X^*, Y, Π, K)
    - if both X^* and Y are <u>simulated</u> from an instance of the DH problem, the adversary has solved it (when submitting K)
    - if one of these values is <u>built by the adversary</u>, it corresponds to an active attempt => at most q_s
  - adversary has guessed the password by pure chance: proba $\leq q_s / N$ since, the password is information-theoretically hidden in the simulation

DoS Resistance

- Denial of service attacks
  - The server never acceptes anything, but rather crashes after memory exhaustion
- Use of cryptographic puzzles
  - Client has to perform a (small) exhaustive search
  - Server can easily solve the correctness

Client		Server
	A →	
	← S, P, cookie	P=*instance*, cookie=MAC(A,S,P)
Find r: $P(r)=0$ Pick x, $X=g^x$	A, X^*, P, r, cookie →	$P(r)=0$? r fresh ? cookie?=MAC Pick y, $Y=g^y$, $K=X^y$
	← S, Y, Auth$_s$, P	
	A, Auth$_A$, P →	

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Conclusion

- One-Mask and Two-Mask EKE variants are
  - provably secure in the random oracle model
  - semantic security
  - unilateral or mutual authentication
- More efficient than EKE
  - only one flow is encrypted
- More suitable for client-server schemes
  - the server can first send a generic flow not encrypted, and thus independent of the client